

[54] LOW FREQUENCY PAPER TRANSIENT FILTERS

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[52] U.S. Cl. 333/76, 333/12, 333/70 R
[51] Int. Cl. H03h 7/04, H04b 15/00
[58] Field of Search 333/76, 70, 12

[56] References Cited

FOREIGN PATENTS OR APPLICATIONS

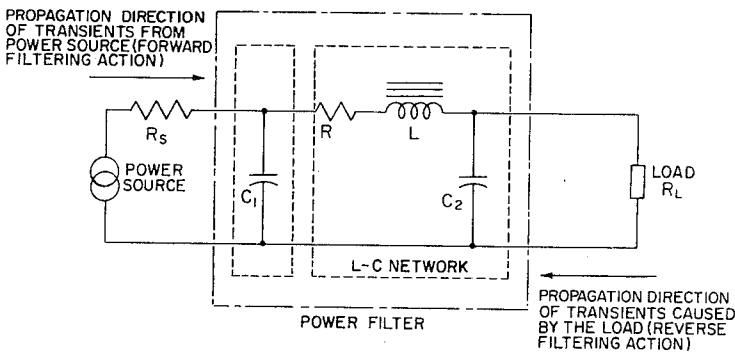
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[57] ABSTRACT

Transients in electrical power systems are capable of causing operational malfunctions in, and possible damage to, delicate equipment such as computers and data processing apparatus. The present disclosure is directed to the design of an inductance-capacitance filter which effectively suppresses externally-produced transients as well as those generated within the load itself.

5 Claims, 10 Drawing Figures



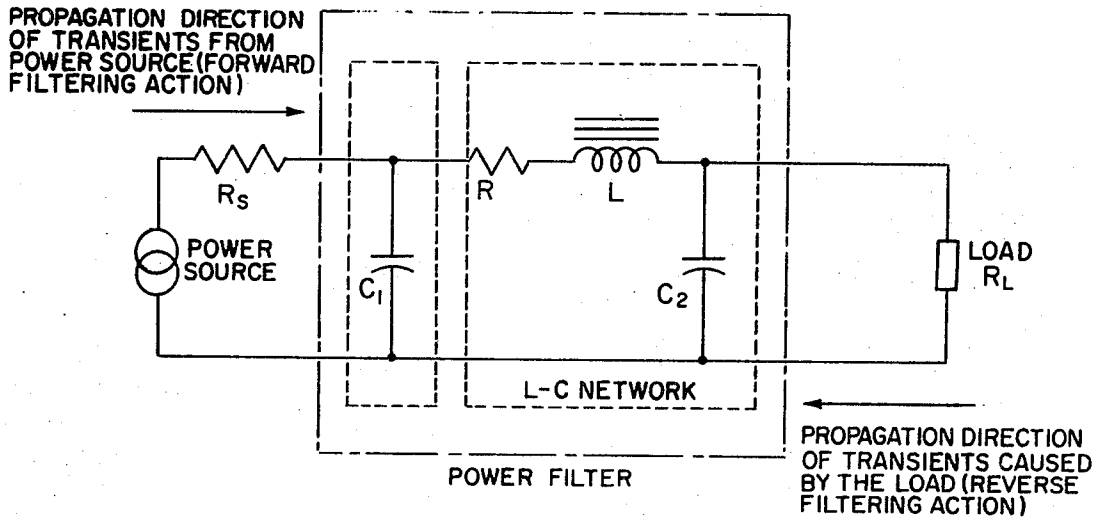


Fig. 1

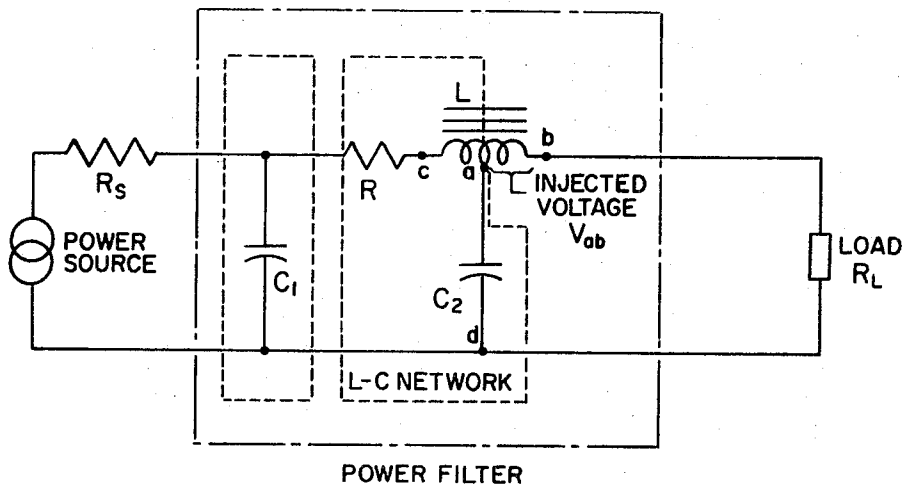


Fig. 7

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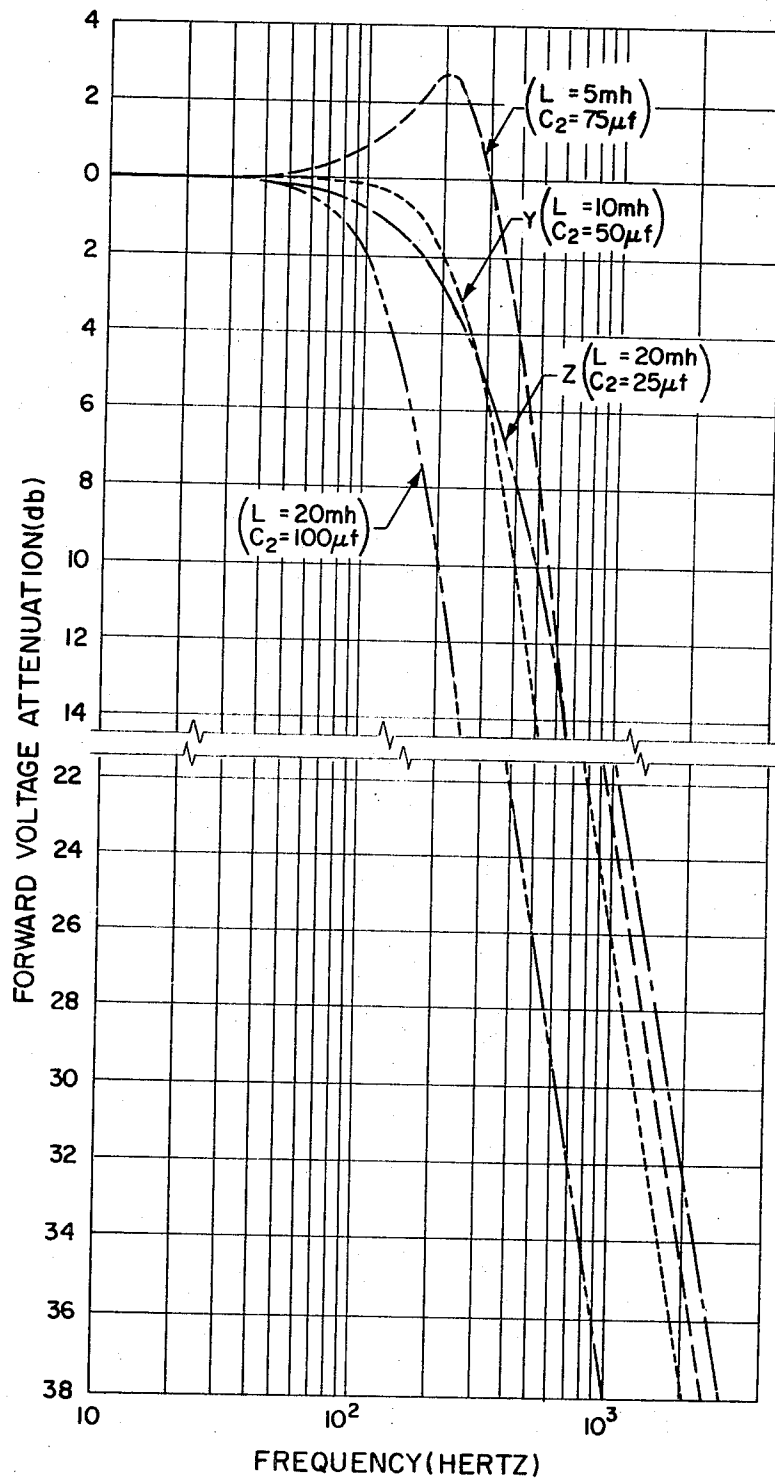


Fig. 2

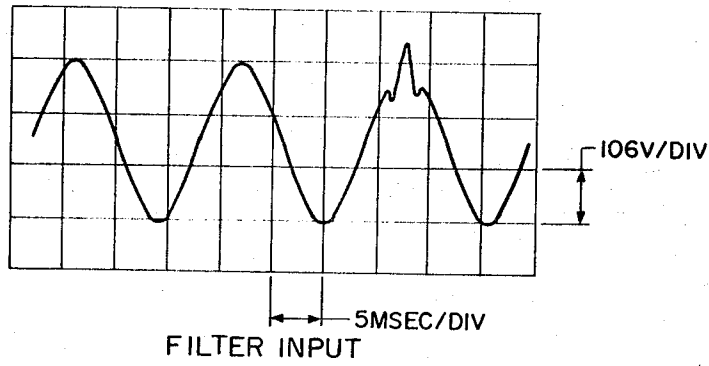


Fig. 3a

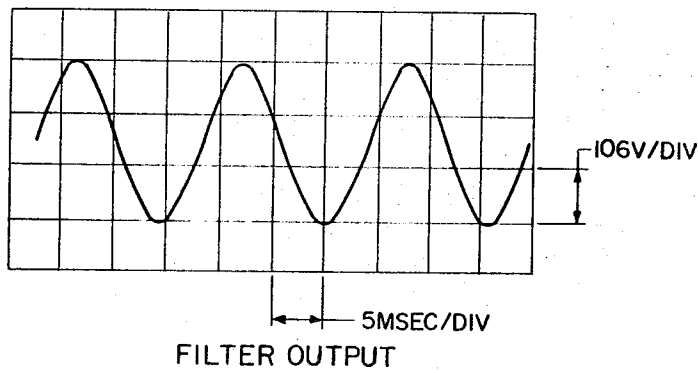


Fig. 3b

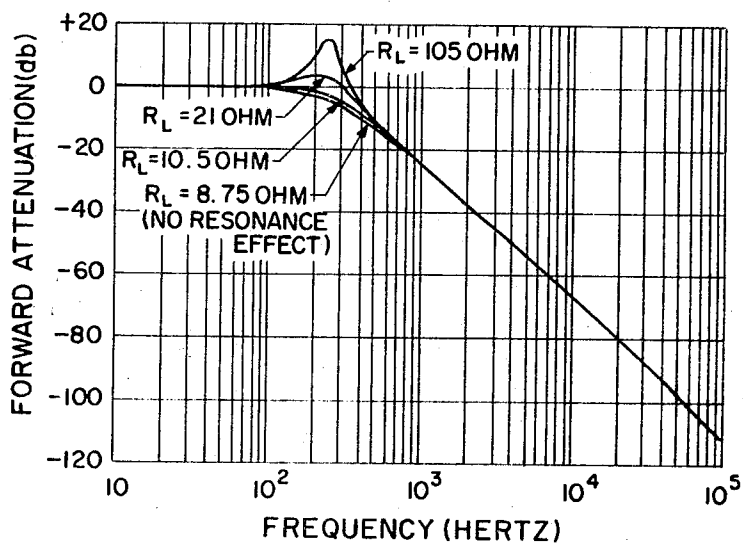


Fig. 6

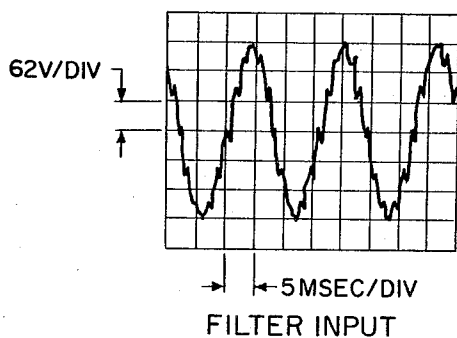


Fig. 4a

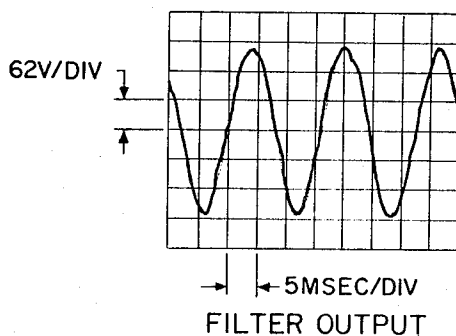


Fig. 4b

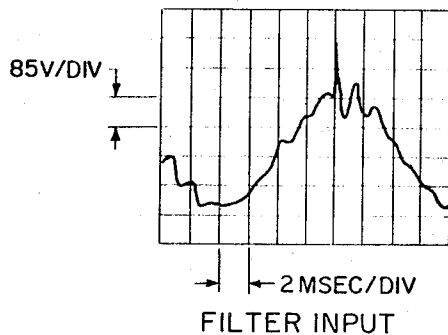


Fig. 5a

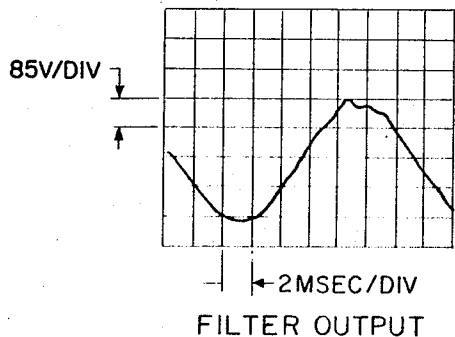


Fig. 5b

LOW FREQUENCY PAPER TRANSIENT FILTERS

STATEMENT OF GOVERNMENT INTEREST

The invention described herein may be manufactured and used by or for the Government of the United States of America for governmental purposes without the payment of any royalties thereon or therefor.

BACKGROUND OF THE INVENTION

Oscilloscope recordings show conclusively that transients in electrical power systems consist of voltage spikes and dips varying in both magnitude and duration. They are usually characterized by a very fast rise time of between 10 and 100 μ sec., and ordinarily are in the form of an oscillatory voltage superimposed on the basic 60-Hertz sine wave. The frequency of these disturbances customarily varies from a few kilocycles down to about 300 Hertz. Those from external sources are a primary cause of computer operational problems, while those generated internally can result in the malfunctioning of synchronous communications equipment.

Power filters which are employed to suppress such transients must satisfy a number of requirements. Not only must they attenuate the disturbances to a level harmless to the load without at the same time appreciably reducing the 60-Hertz line voltage, but they must also produce a minimal rise or drop in the output voltage as the load varies from light to full. In addition, they should not overheat under full-load operation, and should be economical, simple, compact and rugged with a high reliability factor and long operating life.

SUMMARY OF THE INVENTION

The present concept is directed to the provision of a basically two-element inductance-capacitance filter capable of protecting electronic equipment against commonly-occurring harmful power transients. With the addition of a capacitor across the filter input, load-originated disturbances are effectively precluded from being fed back onto the input power lines.

STATEMENT OF THE OBJECTS OF THE INVENTION

One object of the invention, therefore, is to provide means for suppressing low-frequency transients in power lines.

Another object of the invention is to provide a two-element inductance-capacitance filter capable of protecting electronic equipment against externally-produced transients as well as those generated within the load itself.

An additional object of the invention is to provide a filter of the type described that is capable of yielding effective no-load to full-load voltage regulation.

A further object of the invention is to provide a filter of the type described which is not only simple and rugged but which possesses high reliability and a long operating life.

Other objects, advantages and novel features of the invention will become apparent from the following detailed description of the invention when considered in conjunction with the accompanying drawings wherein:

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a circuit diagram of a filter network designed in accordance with a preferred embodiment of the present invention;

FIG. 2 is a set of voltage attenuation curves for the circuit of FIG. 1;

FIGS. 3(a), 3(b), 4(a), 4(b), 5(a) and 5(b) are waveforms of voltages appearing at the input and output terminals, respectively, of the filter network of FIG. 1;

FIG. 6 is a chart illustrating the effect of load variations on the attenuation characteristics of the filter network of FIG. 1; and

FIG. 7 is a modification of the circuit of FIG. 1 to achieve voltage regulation during changes in load impedance.

DESCRIPTION OF THE PREFERRED EMBODIMENT

In designing an inductance-capacitance filter in accordance with the principles of the present invention, it is necessary, in order to obtain maximum transient attenuation, to select a cut-off frequency substantially below the lowest frequency component of the transients to be suppressed. However, the requirement for non-amplification and non-attenuation of the 60 Hertz line voltage places a limit on the selection of the lowest possible cut-off frequency. Also, to prevent overheating, proper choice of wire size for the inductor is essential, and, moreover, a capacitor with low dielectric loss is called for. The economy, simplicity, compactness and ruggedness requirements dictate a passive component design having a minimum number of elements.

The inability of resistance-capacitance filters to provide a low cut-off frequency rules out their use for the purposes herein set forth. However, the two-element L-filter network disclosed possesses the necessary simplicity, economy and compactness to satisfy the demands imposed by the widely-different types of installations where delicate equipment is operated.

A preferred form of filter network, together with its terminal impedances, is illustrated in FIG. 1 of the drawings. The impedances R_s and R_L represent the internal source impedance and the load impedance, respectively. This L filter is capable of suppressing transients propagating towards the load designated as forward filtering action. The capacitance C_1 is added to the filter network to suppress transients that may originate on the load side and propagate back onto the critical bus, designated as reverse filtering action. By this network arrangement, forward and reverse filtering action is achieved.

The forward voltage attenuation characteristics of the filter network of FIG. 1 are given by Equation 1:

$$\alpha_1 = 20 \log_{10} \frac{E_s}{E_L} = 20 \log_{10} \left[\frac{[(R_L + X_{C_2})(R + X_{C_1} + X_{C_2} + X_L) - X_{C_2}^2]}{(R_s + X_{C_1}) - X_{C_1}^2(R_L + X_{C_2})} \right] \quad (1)$$

where α_1 = forward voltage attenuation

E_s = input voltage

E_L = load voltage

$X_{C_1} = 1/j\omega C_1$ = capacitive reactance

$X_{C_2} = 1/j\omega C_2$ = capacitive reactance

$X_L = j\omega L$ = inductor reactance

R = inductor resistance

With R_s and R_L as known parameters, and by varying L and C_2 in Equation 1, a set of voltage attenuation curves is obtained. From this set the best attenuation curve that satisfies the filter requirements is selected. The proper values of inductance L and capacitance C_2 are then determined.

Since the internal power source impedance R_s is usually much less than unity, Equation 1 may be reduced to Equation 2 and X_{C_1} vanishes:

$$\alpha_1 = 20 \log_{10} \left[\frac{R_L(R + X_L + X_{C_2}) + X_{C_2}(R + X_L)}{R_L X_{C_2}} \right] \quad (2)$$

X_{C_1} is essential only for reverse filter action; capacitor C_1 can be eliminated if reverse filter action is not needed.

The reverse voltage attenuation, α_2 , is given by

$$\alpha_2 = 20 \log_{10} \left[\frac{[R_L(R + X_L + X_{C_1} + X_{C_2}) + X_{C_2}(R + X_L + X_{C_1})]}{X_{C_1} X_{C_2}} \right] \quad (3)$$

where R_i = internal transient source impedance.

The dominant factor in Equation 3 is X_{ci} . The value of C_1 depends on the frequency of the fundamental component of the transients, f_t , created by the load. The value of the capacitance C_1 is not critical and it may be selected by choosing the resonant frequency of the LC_1 circuit to be equal to $\frac{1}{2}f_t$. C_1 is given by Equation 4:

$$C_1 = \frac{1}{L f_t^2} \quad (4)$$

FIG. 2 shows a set of voltage attenuation curves obtained by solving Equation 1 for a 10-ampere, 120-volt filter. Each curve represents a possible design value for L and C_2 . In solving Equation 1, R_s is assumed to be constant and is given the realistic value of 0.01 ohm. R_L is taken to be 10.4 ohms and the inductor resistance R is taken as 0.01 ω /mh.

It can be seen from the voltage attenuation curves of FIG. 2 that the cutoff frequency is decreased by increasing the values of either L or C_2 . In addition the choice of values for L and C_2 , and thus the cutoff frequency, is greatly limited by the requirement of nonappreciable voltage loss of gain at 60 Hertz. The attenuation performance of this filter in the frequency range of interest is typically 40 db per decade slope.

FIG. 3(a) of the drawings shows an oscilloscope recording of the transients produced by a utility company switching on 100-kva power factor correction capacitors. FIG. 3(b) illustrates the manner in which the filter network of FIG. 1 effectively suppresses such transients.

FIGS. 4(a) and 4(b) illustrate the effective suppression by the circuit of FIG. 1 of low-frequency transients which cause considerable distortion of the input waveform. FIGS. 5(a) and 5(b) present a similar comparison of filter input and output waves when the former contains a high-voltage pulse associated with a low-frequency oscillation.

The two-element L -filter of FIG. 1 acts to maintain the output voltage relatively constant as long as R_L does not vary. However, if the load does undergo variations for any reason, the attenuation characteristics of the filter of FIG. 1 will be as shown in FIG. 6 of the drawings for representative conditions.

However, since the load voltage is a function of the load current passing through the inductor L , it is possible to achieve a constant load voltage E_L by use of the circuit illustrated in FIG. 7 of the drawings.

In such Figure, the inductor L is effectively divided into two portions $a-c$ and $a-b$ by connecting the capacitor C_2 to a tap at point a . Thus only portion $a-c$ lies within the $L-C$ network. For an inductor of 80 turns, the portion $a-c$ should consist of approximately 60 turns and the portion $a-b$ of approximately 20 turns.

The voltage V_{ab} developed across that portion $a-b$ of inductor L lying outside the $L-C$ network varies in both magnitude and direction as the load changes. For example, when the load R_L increases, V_{ab} also increases. This voltage V_{ab} is injected into the filter output to compensate for the voltage drop V_{ad} on capacitor C_2 . Consequently, the load voltage (which is the vectorial summation of V_{ab} and V_{ad}) remains constant within about 1 percent.

The attenuation performance for a 10-ampere, 120-volt filter is shown in FIG. 2. Each attenuation curve Y and Z represents a possible design value for L and C_2 . The design attenuation curve must be selected to satisfy the filter requirements described previously. The selection criteria may be summarized as follows:

1. The attenuation curve should not have any voltage gain at any frequency. This guarantees the suppression of all transient harmonics as well as avoiding the amplification of any harmonics that may exist in the power supplied.
2. There should not be any appreciable voltage loss or gain at 60 Hertz.
3. The cutoff frequency should be lower than the fundamental component frequency of the incoming transients.

Attenuation curves Y and Z satisfy all design criteria. They establish an inductance L of about 10 mh and a capacitance C_2 between 25 and 50 μ f. The cut-off frequency of the filter is 220 Hertz, which is far below the lowest transient normally present.

In order to lower the cut-off frequency of the filter and thus suppress harmful transients in this region, it was found necessary to employ a specially-designed inductor together with a high-value capacitor. In contrast to the usual powdered iron inductors utilized in filters of this type, it was discovered that one with a laminated iron core would yield a larger value of inductance. However, the presence of both high capacitance and high inductance caused the no-load to full-load regulation to be less than completely satisfactory.

To overcome this condition, the circuit of FIG. 7 was devised, incorporating a "split" inductor one part of which is employed to inject a voltage into the basic $L-C$ filter output. The magnitude and direction of this injected voltage depends on the load current, on the mutual inductance between the two portions of the inductor, and on the ratio therebetween. When such factors are properly related, the circuit of FIG. 7 acts not only as a low cut-off frequency filter but also as a voltage regulator.

In choosing an inductor, the following factors must be considered:

1. The inductor should be as linear as possible. 2. It should not saturate at full load. 3. It should carry the full load on a continuous basis without appreciable heating.

Inductor linearity is usually obtained so that the inductance value is relatively independent of the property of the core material. In the basic inductance design formula, Equation 5, if l_g is chosen much larger than l_c/μ_Δ , the inductance L is determined primarily by the air gap, and the effect of the

nonlinear iron core permeability μ_Δ becomes negligible.

$$L = \frac{3.19 N^2 A_c \times 10^{-8}}{l_g + \frac{l_c}{\mu_\Delta}} \quad (5)$$

where A_c = core cross-sectional area

N = number of turns of inductor

l_c = iron core length, in.

l_g = length of inductor air gap

μ_Δ = incremental permeability of the iron core

To prevent iron core saturation, the flux density at full load, B_{ac} , must not exceed the saturation value. The full-load flux density is computed from Equation 6.

$$B_{ac} = \frac{3.49 E \times 10^6}{N f A_o} \quad (6)$$

where $E = I \omega L$

I = the full load current

$\omega = 2\pi f$ radian frequency

B_{ac} = full load flux density in gauss

The heating problem can be eliminated by minimizing the copper losses. This is achieved by selecting the proper wire size to obtain a low-resistance coil. For the 10-mh, 10-ampere inductor a 12-AWG wire should be chosen. The resistance for this wire is 0.00162 ω /ft. It was determined from conventional inductor design procedures that a 78-turn coil should be wound on a 1.5-inch stack of standard 150 EI selection laminations. The resistance of this coil is calculated as 0.1 ohm. The air gap of the inductor is calculated as 0.030 inch to obtain 10 mh and assure linearity. With 10 amperes flowing at 60 Hertz, the voltage across the 10-mh inductor is 37.7 volts. Substituting into Equation 6, the full load flux density is 14,500 gauss, which is below the saturation value of 16,000 gauss.

Obviously many modifications and variations of the present invention are possible in the light of the above teachings. It is therefore to be understood that within the scope of the ap-

pendent claims the invention may be practiced otherwise than as specifically described.

I claim:

1. Apparatus for suppressing power line transients in the frequency range extending from several kilocycles to approximately 400 Hertz, said apparatus being effective to attenuate transients propagating toward a load as well as those originating on the load side and propagating back toward the power line source, said apparatus comprising:

a filter network connected between said power line source and said load, said network including a series inductor L and a shunt capacitor C_2 ;

a further shunt capacitor C_1 interposed between said filter network and said power line source;

the forward voltage attenuation characteristic α_1 of said apparatus being given as

$$\alpha_1 = 20 \log_{10} \frac{E_S}{E_L}$$

$$= 20 \log_{10}$$

$$\left[\frac{[(R_L + X_{C_2})(R + X_{C_1} + X_{C_2} + X_L) - X_{C_2}^2](R_S + X_{C_1}) - X_{C_1}^2(R_L + X_{C_2})}{R_L X_{C_1} X_{C_2}} \right]$$

where

α_1 = forward voltage attenuation

E_S = input voltage

E_L = load voltage

$X_{C_1} = 1/j\omega C_1$ = capacitive reactance

$X_{C_2} = 1/j\omega C_2$ = capacitive reactance

$X_L = j\omega L$ = inductor reactance

R = inductor resistance

R_S = power line source resistance

R_L = load resistance

and with the reverse voltage attenuation characteristic α_2 being given as

$$\alpha_2 = 20 \log_{10} \left[\frac{R_t(R + X_L + X_{C_1} + X_{C_2}) + X_{C_2}(R + X_L + X_{C_1})}{X_{C_1} X_{C_2}} \right]$$

where R_t = internal transient source impedance

the respective values of inductor L and capacitor C_2 being selected to yield optimum suppression of power line transients

as indicated by the voltage attenuation curve plotted for the particular values of inductance and capacitance so selected.

2. Apparatus according to claim 1 in which said inductor is of the high-permeability laminated iron core type.

3. Apparatus according to claim 1 in which inductor L has a value of approximately 10 millihenries and capacitor C_2 has a value of between 25 and 50 microfarads, yielding a filter cut-off frequency of approximately 220 Hertz.

4. Apparatus according to claim 1 in which the shunt capacitor C_2 is connected to a point on inductor L intermediate the ends thereof, the voltage developed on that portion of the inductor between such point and the end nearest the load being in effect injected into the output of the filter network to compensate for changes in the voltage developed on capacitor C_2 in response to variations in said load.

5. Apparatus according to claim 4 in which the two portions of said inductor lying on opposite sides of said capacitor con-

nection point have a ratio of approximately 3:1, the smallest portion lying on the load side of such point.

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